THE PERUVIAN EARTHQUAKE OF MAY 9TH, 1877.

By J. Milne.

Introduction.

The following account of the Peruvian Earthquake of May 9th, 1877, I have divided into three parts:—

1st.—A tabulation of phenomena connected with the earthquake which appear to be of scientific value.

2nd.—The determination of the origin of the earthquake and the time at which it took place.

3rd.—Notes on the earthquake waves which from time to time cross the Pacific Ocean.

This paper was commenced shortly after an overland journey to Hakodate in 1877. In consequence of not being able to obtain in Japan several works of reference, the chief of which being the "Encyclopedia Metropolitana," the paper was subsequently forwarded to England, where the necessary references were very kindly made for me by my late colleague, Mr. John Perry, for doing which I tender him my best thanks.

Some of the remarks which I make respecting the importance of tide observations in Japan, may be thought to be somewhat far removed from the actual subject under consideration, namely the recording of earthquake waves. Should they however only form a fractional part of the arguments which will sooner or later give rise to the establishment of systematic tide observation in Japan, I shall feel that they have been of more importance than the paper to which they are relatively but an unimportant epilogue.

Part I.

The Phenomena which Accompanied the Earthquake.—On May 11th 1877 the whole of the eastern side of Japan was visited by a series of rapidly recurring tides.

These were of an unusual height and in the local papers they were described as ocean waves. From time to time information was received from various points which told of the alarm, and in many cases of the damage, which these rapid risings of the water had occasioned. From previous experience many persons predicted that at some distant point a large earthquake had happened, and a few days afterwards information was received of the earthquake which occured on May 9th 1877 near Iquique in Peru.

Shortly after this, I travelled along a considerable portion of the Eastern coast of Nippon, from Yedo northwards on my way overland to Hakodate. While on this journey I was enabled to collect a few notes in addition to those which had appeared in the local papers. At Hakodate the phenomena which the waves presented had been carefully noted by Capt. T. Blakiston, a gentleman whom I have to thank for all the information I have with regard to that locality. Subsequently I extracted many and varied notes respecting these sea waves and also of the earthquake which occasioned them, from a variety of Newspapers and Magazines. Foremost amongst these I must mention a long article written upon this earthquake entitled "Das Erdbeben von Iquique am 9 Mai 1877 &c.," by Dr. Geinitz of Göttingen, which appeared in Petterman's Geograph; Mitth. Bd. 23. p. 454. This article embodied almost the whole of the extracts which I had previously made, and the following epitome which is given of the phenomena presented at various localities may be almost wholly found in the paper of Dr. Geinitz.

In the tabulation of these phenomena I have only recorded those facts which I think may be of value to any one studying the nature of the earthquake movement.

These principally refer to the time and direction of the shock and details respecting the succeeding sea waves. If detailed and accurate observations respecting the destruction of property, as for instance respecting the overthrow of buildings, could have been obtained, they might have been retained with advantage for the information of those who wish to study earthquakes. As it is however, the accounts which I have read of the earthquake, are only stories of great calamities, which excite feelings of wonder from their magnitude and sympathy for those who suffered.

In the following tabulation of the phenomena, I have commenced with the Eastern shores of the Pacific, from San Francisco in the north, to Arica, Iquique and Valparaiso in the South. These accounts relate partly to the shock and partly to the sea-waves. These are followed by the phenomena which were presented by the sea-waves at various places in the Pacific, of which the Sandwich Islands, New Zealand and Japan are the chief.

My objects in making this compilation although partly on account of the value it has in itself as a reference from which to obtain facts relating to earthquake phenomena in general, is chiefly on account of special deductions which I wish to make with regard to the particular earthquake about which I am now writing.

North and South America.

San Francisco, Fort Point, (37°, 40′ *S. Lat.* 122°, 32′ *W. Long.*—May 10th, 1877. At this place there is a gauge which registers the tide by means of a pencil working vertically against a sheet of paper which by means of clock work moves horizontally. One foot of tide movement gives one inch of movement in the pencil.—On the sheet there is an apparent ebbing for a few minutes and then a sudden rise, and in 1 hour 20 min. there are 6 large waves each of

9 inches. Movements were indicated from 6.18 a.m. on the 10th until nearly the noon of the 15th, but the latter movements were irregular in time and form, and were probably produced by waves which had been reflected. *(See diagram).*

Guerro (Mexico), on May 10th was overflooded.

Supe, 10° 15′ *S. Lat.*—May 9th during the night the sea rose 15 to 20 feet.

Samanco 9° 15½′ *S. Lat.*—May 9th in the night the sea came over a portion of the town. May 10th the sea rose and fell at least 100 feet.

Callao, 12° 4′ *S. Lat.*, 77° 15′ *W. Long.*—May 9th soon after midnight, disturbance in the water; greatest disturbance at 4 a.m. 8.30 p.m. a shock; the disturbance in the water came about 2 a.m.

Pisco, 13° 44′ *S. Lat.* 76° 14′ *W. Long.*—Sea rose at midnight. The largest wave was at 2 a.m.

Arequipa, 16° 16′ *S. Lat.* 71° 58′ *W. Long.*—About midnight a sea wave. Water rose and fell about 6 or 7 feet.

Ilo, 17° 38′ *S. Lat.* 71° 20′ *W. Long.*—8.30 p.m. strong shock. and about midnight a sea wave.

Santa Rosa (on a steam-ship).—Left Arica about 8.40 p.m., and a few minutes after felt a shock and a sea wave.

Mollendo, 17° *S. Lat.* 72° 2′ *W. Long.*—May 9th, 8.30 p.m., strong earthquake.

Tacna, 18° 2′ *S. Lat.* 70° 13′ *W. Long.*—8.30 p.m., a shaking lasting 2. minutes.

Arica, 18° 28′ *S. Lat.* 70° 24′ *W. Long.*—8.30 p.m., a shaking which lasted until 7 a.m. Sea broke in 8 times, reaching a height of 39 feet. May 10th 4 a.m. was the greatest wave. One observer says the first shock was at 8.25 p.m. and in a North and South direction.

Cabo.—At 8.30 p.m., a shock lasting 2½ minutes.

Coquimbo (on a steam-ship), near Cabo Gordo. At 8.31 p.m. felt a strong shock lasting 55 seconds.

Pisagua, 19° 36½′ *S. Lat.* 70° 19′ *W. Long.*—Sea rose 17 feet.

Mexillones (Peru), 19° 50′ *S. Lat.* 70° 12′ *W. Long.*—May 9th, 8.15 p.m. the earth trembled for 5 minutes. At 11 p.m. the sea rose and inundated the town, the water rising 8 or 9 feet.

Iquique, 20° 12½′ *S. Lat.* 70° 14′ *W. Long.*—On the evening of the 9th May, an earthquake movement was felt. Different observers give the time of this at 8.15 p.m., 8.22 p.m. and 8.25 p.m. Dr. Geinitz takes 8.20 p.m. as being about the time. The movements were at first feeble and slow, and then became one observer says, too violent to stand. One writer says they were from S.W. to N.E. another says from S.E. to N.W. Different accounts give from 3 minutes to 5 minutes as the period of their duration.

Twenty minutes after the first movement the sea rose. Between 8.25 and 10.10 p.m. there were 4 large waves. Altogether during the night the sea broke 8 times over the town. Its greatest height was 20 feet. Some accounts say 65 feet, 30 feet of which was above the highest tide.

San Pedro, 25 to 30 miles S.E. from Iquique. Elevation 4—5,000 feet. May 9th 8.30 p.m. vertical shocks and then a horizontal movement. First movement lasted 6 minutes. Shocks all night.

Pabalon de Pica, 20° 57′½ *S. Lat.* 70°10′ *W. Long.*—About 50 miles south from Iquique. May 9th about 8.15 p.m. earthquake shock lasting 5 minutes. 8.25 p.m. sea broke in six times. Place destroyed.

Chanabaya, 21° *S. Lat.*—About 8.25 or 8.30 p.m. a shock. Between 8.25 and 10.10 p.m., five waves broke over the town. Shocks continued until 11th May.

Punta de Lobos, 21° 5½′ *S. Lat.*—8.30 p.m. a shock, sea drew back and in 10 min. returned to cover everything 35 feet above the ordinary level. Shocks during the night.

Huanillos, 21° 15′ *S. Lat.* 70°18′ *W. Long.*—8.30 p.m. a shock, immediately followed by a wave 60 feet high. May 15th at 2 a.m. another shock.

Tocopilla, 22° *S. Lat.*—May 9th 8.30 p.m. (or according to another observer 8.5 p.m.) the first disturbance. Then a wave 80 feet high. Some say this came 15 minutes after the shock, and was only 20 feet high.

Cobija, 22° 34′ *S. Lat.* 70°, 21′ *W. Long.*—8.30 p.m. a heavy shock. 8 minutes after the sea rose 30 feet.

Caleta, shock 8.20 p.m. 20 minutes after, sea rose 60 feet. Another account says the first shock was about 8.30 p.m.

Mejillones de Bolivia, 23° 6½′ *S. Lat.* 70° 35′ *W. Long.*—8.15 p.m. shock lasting 7 minutes (?) First it was slow, afterwards strong. The movement changed from South to East.

1st. Wave, 35 feet high, came half an hour after the first movement.

2nd. Wave, 15 minutes after the first wave.

3rd. Wave, 45 minutes after the second.

Another account says the sea rose and fell every 20 minutes.

Caracoles, Shock lasted 7 or 8 minutes.

Antafagasta, 23° 35′ *S. Lat.* 70° 25′ *W. Long.*—May 9th 8.30 p.m. a prolonged shock lasting 5 minutes. Sea rose three times. Another account says the shock was at 8.32 p.m. and lasted 3 minutes. Movements continued until 11 p.m. In 36 hours there were 80 shocks. The movements were from North to South. Another observer says that the movements commenced at 8.35 p.m. and the most violent of them lasted 2½ to 3 minutes. At first the sea did not move until at last it came in suddenly as a large wave.

"*John Elder*" (steamship) when in 23° 43′ *S. Lat* and 70° 47′ *W. Long.* 23 miles west of Antofagasta, at 8.20 p.m. on the 9th May, all on board felt a violent shaking, and the ship was stopped by a shock as if it had struck a rock.

"*Eten*" (Steamship) at anchor at Antafogasta. At 8.15 p.m. a shock which caused the ship to lift its anchor.

Caldera 70° 54′ *W. Long (North from Copiapo).*—May

9th at 8.25 p.m. the earth commenced to tremble. In 1½ minutes the motions reached their maximum. They lasted 2½ minutes. Their direction was from North to South. At 11 p.m. the sea broke in, having first silently drawn back 200 ft. The height of the wave was over 5 feet. The movements were strong until next day. During the night 10 or 15 shocks.

Copiapo, 27° 20′ *S. Lat.* 71° 2′ *W. Long.*—May 9th 8.20 p.m. first movement. This according to one report was from N. to S. according to another from E. to W. Movements continued until 11.30 a.m. on May 10th.

Chanarcillo, 27° 55′ *S. Lat.* 69°, 45° *W. Long.*—Here and at other places, movements from 8.30 p.m. on the 9th May, until the evening of the 10th May.

Carrizal Alto and Carrizal Bajo (S. of Copiapo) 28° 5′ *S. Lat.* 71° 10′ *W. Long.*—At 8.30 p.m. a shock from North to South. Sea drew back and then came in. At 10.30 p.m. the sea drew slowly back, and 10 minutes after rose 4 ft. above the highest tide. It rose and fell for more than three hours.

Vallenar.—May 10th 8.30 p.m. a shock lasting 2 minutes.

Freirina.—At 8.15 p.m. a shock lasting 3 or 4 minutes Until 10 p.m. 4 small shocks.

Chanaral, 29° 2′ *S. Lat.* 71°, 34′ *W. Long.*—May 9th 8.45 p.m. a shock lasting 2 minutes, and the sea retired. 1¾ hours after the sea returned.

An Official report says the shock was at 8.40 p.m. and 3 hours after the sea wave came in. The second wave was larger than the first, its direction was from S. to N.

Another observation gives the 1st shock as being at 8.25 p.m.

Another account says the sea came in at 9.15 p.m. and again about 10.30 or 11 p.m.

Coquimbo, 29° 55′ *S. Lat.* 71°, 24′ *W. Long.*—May 9th. At 8.25 p.m. a shock lasting 4 or 5 minutes. About 10.30 p.m. the sea went back. At 11 p.m. it again went back, and these movements continued until 1 p.m. on the 10th May.

Another observation gives the time of the earthquake as 8.31 p.m., and for its duration 1 minute 58 seconds.

Movement was from N. to S. together with strong impulses from E. to West.

Ovalle.—A shock from N. to S.

Constitucion, 23° 30′ *S. Lat.* 70° 50′ *W. Long.*—May 9th, 10 p.m. an unusual movement in the water was observed.

Valparaiso.—May 9th 8.30 p.m. or 8.25 p.m. a long but light Earthquake. Unusual movement in the sea lasting until 11.

Concepcion, 36° 49′ *S. Lat.* 73° 5′ *W. Long.*—May 9th between 8 and 8.15 p.m. a light but long earthquake.

At Talcahuano N. of Concepcion. About 12 p.m. the sea retired and at 1 a.m. returned 1 mile over High water mark.

8.20 p.m. shock which was slow and long. Four hours after the sea slowly retired, and at 2.30 a.m. slowly returned rising 3 metres above its ordinary level.

Another observer says the shock was at 8.14 p.m. and the first wave came in at 11. The water reached 8 or 10 feet over its highest level.

Between the coming in and going out of the water there was usually from 12 to 15 minutes.

Penco.—At 1 a.m. the sea retired.

Aranco.—(S. of Concepcion) sea retired 1 Legua from the Mouth of the Rio Carampagne.

Lota.—May 10th 2.12 a.m. the sea rose.

Ancud (Ancua), 41° 52′ *S. Lat.* 73° 53′ *W. Long.*—May 9th From 11 p.m. until 3 a.m. an unusual movement in the water. May 10th between 11 and 12 a.m. the sea rose and fell three times.

Sandwich Islands.

Oahu, Honolulu, 21° 28′ *N. Lat.* 157° 55′ *W. Long.*—May 10th 5.20 a.m., sea violent. In 5 min. it fell 21 inches. At 6 a.m. the water came back, and in 10 minutes the sea rose 34 inches. The water was going to and fro day and night, and increasing. The greatest difference was 58 inches. This was during the forenoon.

At the islands of Kauai, Maui and Hawaii, movements were observed.

Hawaii, Hilo 19° 44′ *N. Lat.* 155° 3′ *W. Long.*—Wave came at 4.45 a.m. in a direction N.N.E. from Waiakea. Its height was 30 feet. It rose 16 to 17 feet or 13.5 feet above half tide. Another observer says the unusual oscillation was at 4 a.m. about 1 hour before the great wave whose height was 13 feet 6 inches over low water mark

Sea rose and fell all day. At 7 a.m. there was a great tide. From the lowest point to the highest, it was 4 minutes in rising, the height being 14 feet. All day between rising and falling it was 3 minutes.

At 3 p.m., in 10m. sea rose 6 feet over High Water Mark.

in 10m. more	it fell 2 feet under low	„	„
„ 8m.	„	rose 8 feet above middle	„	„
„ 12m.	„	fell to low water.	„	„
„ 15m.	„	rose 3 feet over high	„	„

and in about 15m. again fell.

It rose and fell three times per hour.

Kawaihae, on W. side of Hawaii.—The sea rose and fell 5 feet.

Kahului, 20° 31′ *N. Lat.* 156° 43′ *W. Long.*—May 10th at 4.45 a.m., the sea went back and then returned quickly 4 or 5 feet over High Water Mark. The second wave was not so high as the first, the third still lower. The fourth was as large as the first.

On May 12th, the sea was also disturbed.

Island of Maui.—May 10th at 6.45 p.m. (a.m.?) the sea subsided.

Owing to differences in the configuration of the coast, outlying reefs and Islands &c., the height to which the water rose at different places considerably varied.

This will be seen from the following table :—

Hilo, E. side of Hawaii	36 ft.	0 in
Kawaihae, W. side of Hawaii	5	„
Kealakeakua Bay, W. side of Hawaii	30	„
Kahulin, N. side of Maui	22	„
Lahaa, S. „ „ „	12	„
Honolulu, S. side of Oahu Island	4	10
Nawiliwili, S. E. side of Kauai	3	„

Speaking generally the sea rose and fell all day. At 7 a.m. it rose and fell about 14 feet in 4 minutes. In the afternoon it rose and fell 10½ feet, 3 times.

The first and strongest waves came upon the South and East portion of the Islands.

South Pacific.

Samoa Islands, *Apia*. 13° 49′ *S. Lat.* 171° 41′ *W. Long.*—May 11, 4½ a.m. (at ebb tide) a sea wave. About 6 a.m. it was strongest, rising and falling about 12 feet. This rising and falling continued about every 10m. About 8 a.m. it rose and fell about 6 feet, but was neither so strong nor so quick. This lasted until about 12 (flood tide) when it died out gradually.

Tawera, (a Brigantine) in 35° 30′ *S. Lat.* 104° 52′ *W. Long.*—On May 8th at 4 p.m. felt a strong shock.

Chatham Islands.—During the night of May 11th, a sea wave.

New. Zealand.

May 11th about 7 a.m. a rising and falling of between 3 and 8 feet was observed in the sea at many places. Between the rising and falling the time varied from 15 minutes to an hour.

Aukland.—May 11th the wave rose 11 feet.

Tauranga, 37° 37′ *S. Lat.* 176° 11′ *E. Long.*—May 11th about 8 a.m. Water rose 3 feet over the usual spring tide. All day it rose and fell.

Poverty Bay, *Gisborne*. 38° 40′ *S. Lat.* 178° *E. Long.*—Night of May 11th, a large wave. Morning of May 11th

(12th ?) 3 a.m. at ¾ ebb tide, a wave caused the river to rise 3 to 4 feet. 9.30 a.m. a second wave; 9.45 a.m. a third and soon after a fourth.

Wellington, 41° 6′ *S. Lat.* 174° 30′ *E. Long.*—May 11th just before 7 a.m. at a little past ¾ ebb tide, a large sea wave came in. In ¼ hours the water rose above high water mark; 15 minutes after it was at low water mark. From 7.45 a.m. to 9.50 a.m. it gradually decreased. At 8 a.m. the difference in level was nearly 5 feet and at 10 a.m. 2 feet.

Up to midday the interval between the rise and fall was 7 minutes, and the height was 1 foot. Movement all day. From 7 a.m. to 3 p.m. the water rose and fell 20 times.

Cook Straits.—On Friday May 11th ? (Sunday) movement observed. The waves came from the S.S.E; another observer says from the West.

Buller River, West Coast.—Movements in the water were observed.

Kaiapoi (N. from Lyttelton).—May 12th, 3 miles up the river the water rose 2 to 3 feet. 1st wave at 6 a.m. and between this and 8 a.m. 3 other waves.

At Kaiapoi on Saturday at midday two waves were observed.

Le Boris Bay.—(East side of Banks Peninsular) May 11th 7 a.m. unusual waves which retired rapidly were observed. At midday a large wave.

Akaroa, 43° 51′ *S. Lat.* 172° 59′ *E. Long.*—Sea waves commenced at 1 a.m. (7 a.m.?) they continued until 3 p.m. when they were greatest, reaching 10 feet over high water mark. At 5 p.m. they died away.

Timaru.—Waves first observed at 7 a.m. The motion continued until late in the afternoon.

Port Chalmers.—Movement first noticed at daybreak, it being of about 1 foot. In the early forenoon there was a sudden rising and falling from 7 to 20 feet, lasting several hours.

Lyttelton, 43° 37′ *S. Lat.* 172° 45′ *E. Long.*—In the early morning unusual conditions were observed. At 7 a.m. in 7 minutes the water rose 18 inches. At 9 a.m. it rose and fell 3 ft. in 5 minutes—later 3 feet in 2 minutes.

Movement continued until night.

Omaru.—The water went to and fro about every 15 minutes. At 12 o'clock (noon) it was violent, coming into the bay. It went out again a few minutes after. At 12.30 p.m. the movement was over.

AUSTRALIA.

Sydney.—May 11. The water rose suddenly more than 2 feet and then retired.

Newcastle, in 5 minutes the sea fell 20 feet.

JAPAN.

I obtained records of a series of sea waves which came in at many places along the Eastern coast.—Of these there are only two which are of any value, namely those made at Kamieshi and those at Hakodate.

Kamieshi, 39° 18′ *N. Lat.* 140° 50′ *E. Long.*—May 11th. In the morning the sea rose and fell from an extremely low point to an extremely high one. The motion was very gentle and only just perceptible. It was like an extraordinary tide. The movements were first noticed about 10 a.m. At 12 o'clock they were quite rapid, occurring about every 15 minutes. As marked upon a jetty the water rose about 5½ feet above ordinary High Water Mark. About 6 p.m. it rose only every half hour, and then only about 2½ or 3 feet.

Although some rocks lying several miles out at sea were carefully watched with a telescope, no tendency to banking could be observed. During the whole day the sea was as smooth as a looking glass. The people were frightened and fled from the village with their goods towards the hills. About 45 years ago the sea had been similarly disturbed.

Hakodate.—May 11th, 41° 50′ *N. Lat.* 140° 50′ *E. Long.*—At 11.30 a.m. the sea suddenly receded and 10 minutes after rose again with a swell of 7 feet. It continued to rise and fall at intervals of about 20 minutes.

At about 2.30 or 2.35 p.m. it reached its maximum, overflowing the bund and a portion of the town. From this time it gradually diminished and in the evening all was calm and still.

It was felt all along the coast to Nagasaki, and at many places the people were so alarmed that they moved their goods towards the hills. The oscillation was greatest about 2 p.m. In some places it was said to rise and fall about 10 feet every 5 minutes.

PART II.

Determination of the origin of the Earthquake.

Looking over the various records which have just been given we see that the shock was first felt in the neighbourhood of Iquique. If we convert the local times which are given for the 1st shock into Iquique time, we have the first shaking occurring as follows.

Iquique	8 hr.	20 m.	0 sec.	p.m.
	8 „	25 „	0 „	„
Pabalon de Pica	8 „	15 „	2 „	„
Chanabaya	8 „	25 „	6 „	„
	8 „	30 „	6 „	„
Punta de Lobos	8 „	30 „	2 „	„
Huanillos	8 „	30 „	0 „	„
Tocopilla	8 „	30 „	2 „	„
	8 „	5 „	2 „	„
Cobija	8 „	30 „	24 „	„
Mejillones	8 „	16 „	20 „	„
Caldera	8 „	27 „	38 „	„
Copiapo	8 „	23 „	0 „	„

From this it would seem that the origin of the shock was nearer to Pabalon de Pica than to Iquique.

The direction in which the shaking is recorded as having taken place also indicates that the origin lay to the South of Iquique.

If we look at the times of arrival of the first sea wave we shall also see that the origin is nearer to Pabalon de Pica than it is to Iquique.

Also, we shall observe that with the single exception of Huanillos the sea wave came some time after the earth shock. Because the wave motion from an earthquake shock travels more quickly through rock than it does through water, we should infer from this that the shock had its origin at some point beneath the ocean. It seems therefore very probable that the center of the shock lay somewhere westerly from Pabalon de Pica, beneath the bed of the Pacific, and this is all that it seems possible to infer from the preceding tables as to the position of the origin by simple inspection. Many of the accounts of this earthquake refer to the volcano Iluga (Isloga) to the west of Iquique as the origin of all these disturbances, but for this supposition no definite reasons are given.

So far as the determination of the origin of the shock from a simple inspection of the various records is concerned, we see that we are not able to define its position with any accuracy. All that we can say, is that it originated beneath the ocean, westward from Iquique or Pabalon de Pica. Further we shall observe that on account of the peculiar geographical distribution (along a North and South line) of the places at which many of the records were made, the ordinary methods which we have at our command for the determination of the origin hardly appear to be applicable. The indefinite result at which we may arrive with respect to the position of the origin by using an ordinary method for its determination may be judged of from the first of the methods which are employed.

From the various times which are given for the arrival of the shock or-sea wave at any place, when making calculations, I have taken those which seemed to be most probably correct, in preference to taking the mean of several observations. Thus, for instance, I have taken the time given in an official report rather than that which has been given by an ordinary observer. Notwithstanding these precautions, it is very evident by glancing at these times and by remembering what has already been said as to the probable position of the origin of this earthquake, that most of the given times are wrong one or two minutes, and several of them perhaps half an hour or more. These latter I have altogether omitted.

On the accompanying plate the position of a number of the more important places are represented in orthographic projection, the center of projection being near the center of the map. This projection has been used because it was thought that any geometrical measurements made upon such a map would be more correct than those taken from an ordinary chart, in which this portion of the earth is not taken as the center of projection.

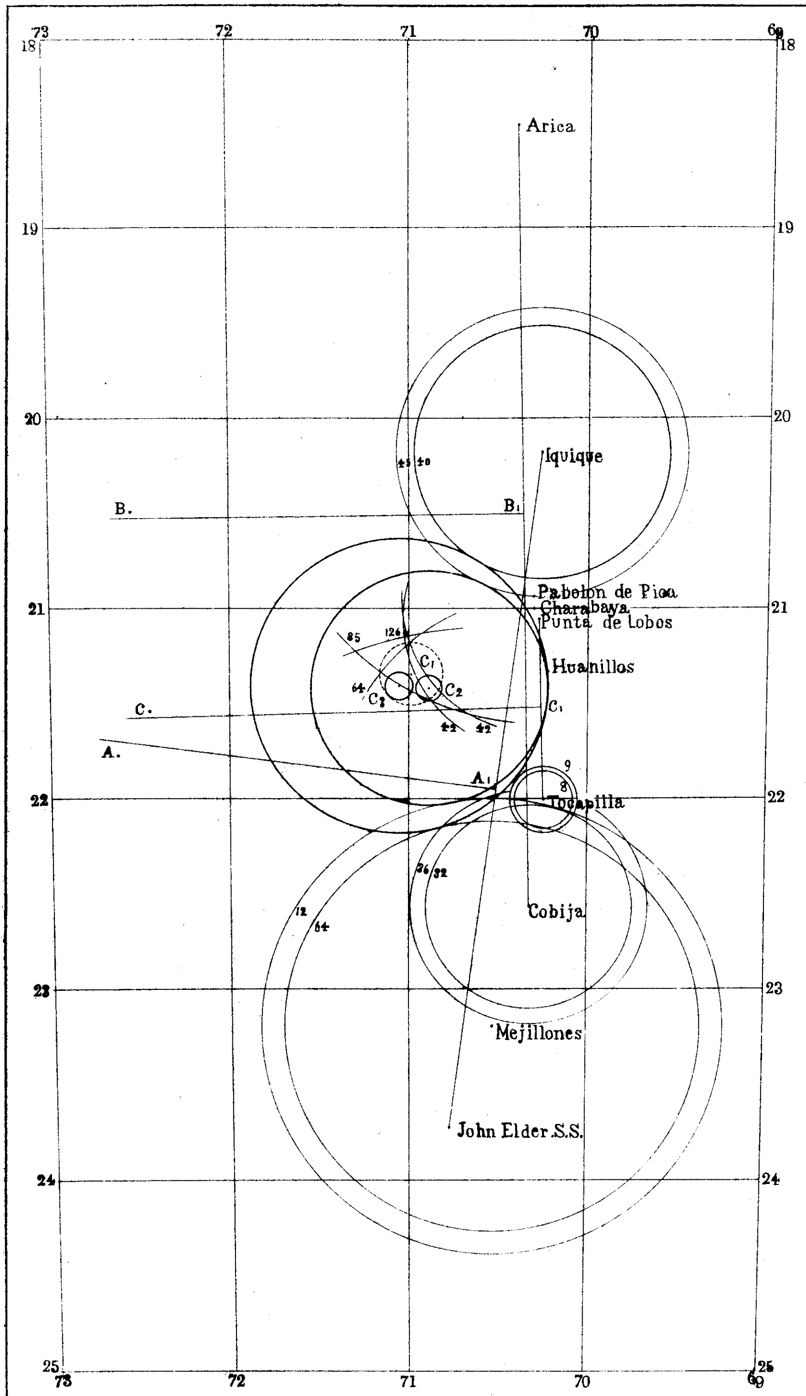
By looking at the column which gives the difference in time between the arrival of the shock and the sea wave (see table page 73) it will be seen that in all cases a considerable interval of time elapsed, indicating that the origin of the shock was at some distance.

And because the depth from which the shock originated as compared with the horizontal distances measured to the places where it was felt, must from all we know, be probably insignificant, the horizontal distance to a point immediately above the origin, that is to the *Epicentrum*, and the direct distance to the origin itself, will be considered as being equal. In the following determinations, therefore, it is the point immediately above the origin which is determined rather than the origin itself.

Because the places referred to are probably some distance away from the origin, the absolute velocity will be so little different from the horizontal velocity that the two will be considered as being equal.

When speaking of the sea wave it will naturally be the horizontal propogation that is treated of.

In the calculation with regard to the velocity, it is assumed that the rocks lying between the origin and the various



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Determination of the Origin.

places which are used in the calculations, have a general similarity, and that therefore the rate of propogation to the different places may be indicated by the same number.

Considering the short distances between the places which are chosen and their position with regard to the probable position of the origin, this assumption will be seen not to be an unfair one.

When speaking of the rate at which the sea wave travelled to the various places which are used in calculating the position of the origin, this also will be supposed to be constant. If these places were far apart and the ocean which lay between them was of different depths, we see that such an assumption would not have been admissable, because it is possible from the depth of the ocean to find a fair approximate to the velocity with which a wave will be propogated, and therefore there would not have been any necessity to assume the propogation to have been constant.

I. Method. *Given a number of pairs of points* A_0 A_1, B_0 B_1, C_0 C_1, *etc., at each of which the shock was felt simultaneously, to determine the origin.*

Theoretically if we bisect the line which joins A_0 and A_1 by a line at right angles to A_0 A_1, and similarly bisect the lines B_0 B_1, C_0 C_1, all these bisecting lines a_0 a_1, b_0 b_1, c_0 c_1 etc., ought to intersect in a point, which point will be the *Epicentrum* or the point above the origin.

This method will fail, 1st if A_0 A_1, B_0 B_1, C_0 C_1 form a continuous straight line, or if they form a series of parallel lines.

In the plate I have considered the shock to have arrived simultaneously at Iquique and the Steam Ship John Elder, at Cobija and Arica, and at Tocopilla and Punta de Lobos.

From the inaccuracy in the observation of these times of arrival, it is seen by reference to the plate that these lines A_1 A_0 &c. would not intersect at a point. All that we can say from them is that the origin probably lies somewhere to the left of C_1 C_0. In this particular case therefore the method practically fails. If the times of arrival had been accurately registered by a seismograph, or if the places had been lying more round the center, rather than along a line at one side of it, the method might have given results which were more definite.

Hopkins gives a method based on a principle similar to the one which is here employed, namely, given that a shock arrives simultaneously at *three* points, to determine the center. In this case three points, where the time of arrival was simultaneous, have not been recorded, and even if we had such points, because these three points would have been nearly in a straight line, the method would have failed. For practical application the problem must be restricted to the case of three points which do not lie nearly in the same straight line.

II. METHOD. *To determine the origin of a shock which took place beneath the ocean, giving rise to an earth wave and to a subsequent sea wave, the times of arrival of these two disturbances being noted at several points.*

First let the times of the arrival of these two waves be noted at a number of places A_0, A_1 A_2 etc. Let the difference in time between the arrival of the two waves at $A_0 = t$, at $A_1 = t_1$, $A_2 = t_2$ etc.

Assume the rates at which the earth wave and the sea wave respectively travelled to be V and v.

If x be the distance of the *epicentrum* from A^o.

Then, $$\frac{x}{v} - \frac{x}{V} = t_0$$

Whence $$x = \frac{t_0 V v}{V - v}$$

Similarly if y be the distance of the *epicentrum* from A_1,

Then, $$y = \frac{t_1 V v}{V - v}$$

Similarly the distances of the remaining places A_2, A_3, A_4, etc., from the *epicentrum* may be also found.

With centers A_0, A_1, A_2, &c. and with radii x, y &c., discribe arcs. These will intersect at the point above the origin. In the case of the Peruvian Earthquake, in one set of calculations I supposed the land shock to have travelled at the rate of 1500 feet per second and the sea wave at the rate of 300 feet.

In a second series of calculations the rate of the earth-wave was reckoned at 1000 feet per second. The distances of the center from the following places, as calculated on these assumptions measured in miles, are given in the following list.

	Diff. in time of 2 waves.	At 300 & 1500 ft. per second.	At 300 & 1000 ft. per second.
Iquique	20 m.	85 miles.	96 miles.
Pabalon de Pica ...	10 „	42 „	48 „
Punta de Lobos... ...	10 „	42 „	48 „
Tocopilla	15 „	64 „	120 „
Mejillones	30 „	126 „	144 „
Coquimbo	2 hr. 5 „	525 „	600 „
Concepcion...	3 „ 40 „	945 „	1080 „

On the accompanying plate from these places as centers with the corresponding distances as radii, arcs have been described. In the plate only those of the first column are shown, and of these only the first five. Those arcs are marked with miles corresponding to the places from which they were described. The center thus obtained is marked C_1 and it is indicated by a dotted circle. Those of the second column to avoid confusion are omitted in the drawing. Their intersections although not lying so closely together as the intersections which give C_1 lie very near the same locality.

If we obtain radii by reckoning the velocity of the earth wave to have been 1700 feet per second, the intersections are even closer than in the case of C_1.

Although in both cases the origin is indicated as being in nearly the same locality the locus indicated by C_1 is probably nearer to the truth than C_2.

If arcs were described from Valparaiso, Arica or other places a long distance from the center, the result although pointing in the same direction would be inaccurate. The reason for this lies cheifly in the facts, 1st that the shock which was noted at these places may not have been the same as that registered in the neighbourhood of Iquique, and 2ndly the velocities of the waves (and most certainly that of the sea wave) would be different to the velocities at which they travelled to places in the neighbourhood of Iquique. For these reasons they have been left out.

The chief objection which can be raised to this method of determination will be to the assumption of the velocity at which the waves travelled. With regard to the sea wave we can approximately calculate the rate at which it travelled by noting the time at which it arrived at one or two places near the origin, and the times at which it arrived at distant places. The differences between these times will roughly give the time the wave took to travel a given diss tance, and from this a velocity may be deduced. These places must of course be judiciously chosen. Or if from a chart we know approximately the depth of the water over which the wave travelled, the rate at which a wave travel· in such water is approximately given by Airy's rules (see Encyc: Metrop. Article, Tides and Waves).

With regard to the determination of the rate at which the shock travelled through the rocks there is more uncertainty.

The average rate at which the earthquake of Calabria travelled as calculated by Mr. Mallet, is given at 789 feet per second.

The rate at which the Lisbon earthquake travelled was calculated by Mitchel at 1760 feet per second. At Holyhead the average rate at which Mr. Mallet found a shock was transmitted through granitic rocks was 1320 feet per second.

Others who have observed the transmission of earth vibrations produced artificially or by earthquakes, have calculated velocities which are very much higher than these.

In many cases it might be determined, by first determining by some of the many means which are at our disposal the direction from which the shock originated, and then by calculating the rate at which the shock was propagated between two places lying in the same straight line, as was done by Mr. Mallet when discussing the Neapolitan Earthquake of 1859.

III. METHOD. *Given the times t_0, t_1, t_2, etc., at which a shock arrived at a number of places A_0 A_1 A_2 etc., to determine the position from which the shock originated.*

Suppose A_0 to be the place which the shock reached first, and that it reached A_1 A_2 A_3 etc., successively afterwards.

Let
$$t_1 - t_0 = a$$
$$t_2 - t_0 = b$$
$$t_3 - t_0 = c \text{ etc.}$$

With A_1 A_2 A_3 etc., as centers describe circles with radii proportional to the known quantities a, b, c, etc. and also a circle which passes through A^0 and touches these circles. The center of the last circle will be the *Epicentrum*. The radii proportional to a, b, c, &c., may be represented by the quantities ax, bx, cx, &c., where x is the velocity of propogation of the shock.

It will be observed that the times at which the shock arrived at three places might alone be sufficient. If instead of taking the times of arrival of the shock, those of the arrival of the sea wave be taken, the result will be a closer approximate to the absolute truth. Having thus obtained the center from which a shock originated, we might determine its velocity and the time at which it originated.

On the map this method is illustrated by the complete circles. The places taken are Tocopilla, Iquique, Cobija and Mejillones.

In the following table the first column gives the times at which the sea wave arrived at each of these places in

Iquique time; in the second column the difference between these times and the time at which it reached Huanillos is given; in the third column the distances through which a sea wave propogated at the rate of 400 ft. per second could travel during the intervals noted in the second column is given; and in the fourth column the distances a wave would travel in the same time but at the rate of 350 feet per second is given.

	Arrival of sea wave.	Time after arrival at Huanillos.	Distance at 400 feet per second.	Distance at 350 feet per second.
Huanillos ...	...8 hr. 30 m.	0 m.	0 miles.	0 miles.
Tocopilla ...	...8 „ 32 „	2 „	9 „	8 „
Cobija ...	...8 „ 38 „	8 „	36 „	32 „
Iquique ...	...8 „ 40 „	10 „	45 „	40 „
Mejillones...	...8 „ 46 „	16 „	72 „	64 „

The distances marked in these columns are used as radii of the circles drawn round the places to which they respectively refer.

The centre of the circles drawn to touch the circles of the first column, and at the same time to pass through Huanillos is marked C_2. That which is drawn to touch the remaining smaller circles is marked C_3.

We have here obtained two more centers both of which it will be seen very closely coincide with the one which has been previously obtained.

The position from which the shock originated appears therefore to have occurred very near to a place lying in Long 7°15′ W. and 21°22′ S. Lat.

IV. Method. *Given the times at which a shock arrived at five or more places, the position of which we have marked upon a map, or chart, to determine the position on the map of the center of the shock, its depth, and the velocity of propogation.*

Commencing with the place which was last reached by the shock, call these places p, p_1, p_2, p_3, and p_4, and let the times taken to reach these places from the origin be respectively t, t_1, t_2, t_3 and t_4.

Through p draw rectangular coordinates, and with a scale measure the co-ordinates of p_1 p_2 p_3 and p_4 and let these respectively be, a_1 b_1, a_2 b_2, a_3 b_3, a_4 b_4. Then if x, y, and z be the co-ordinates of the origin of the shock, d, d_1, d_2, d_3, d_4, the respective distances of p, p_1, p_2, p_3, and p_4 from this origin, and v the velocity of the shock, we have

1. $x^2 + y^2 + z^2 = d^2 = v^2 t^2$
2. $(a_1 - x)^2 + (b_1 - y)^2 + z^2 = v^2 t_1^2$
3. $(a_2 - x)^2 + (b_2 - y)^2 + z^2 = v^2 t_2^2$
4. $(a_3 - x)^2 + (b_3 - y)^2 + z^2 = v^2 t_3^2$
5. $(a_4 - x)^2 + (b_4 - y)^2 + z^2 = v^2 t_4^2$

Because we know the actual times at which the waves arrived at the places p, p_1, p_2, p_3, p_4 we know the values $t - t_1$, $t - t_2$, $t - t_3$, $t - t_4$. Call these respectively m, p, q, and r. Suppose t known, then

$$t_1 = t - m$$
$$t_2 = t - p$$
$$t_3 = t - q$$
$$t_4 = t - r.$$

Subtracting equation No. 1 from each of the equations 2, 3. 4 and 5 we obtain,

$$a_1^2 + b_1^2 - 2a_1 x - 2b_1 y = v^2 (t_1^2 - t^2) = v^2 (m^2 - 2t m)$$
$$a_2^2 + b_2^2 - 2a_2 x - 2b_2 y = v^2 (t_2^2 - t^2) = v^2 (p^2 - 2t p)$$
$$a_3^2 + b_3^2 - 2a_3 x - 2b_3 y = v^2 (t_3^2 - t^2) = v^2 (q^2 - 2t q)$$
$$a_4^2 + b_4^2 - 2a_4 x - 2b_4 y = v^2 (t_4^2 - t^2) = v^2 (r^2 - 2t r)$$

Now let $v^2 = u$, and $2v^2 t = w$.

Then

1. $2a_1 x + 2b_1 y + u m^2 - w m = a_1^2 + b_1^2$
2. $2a_2 x + 2b_2 y + u p^2 - w p = a_2^2 + b_2^2$
3. $2a_3 x + 2b_3 y + u q^2 - w q = a_3^2 + b_3^2$
4. $2a_4 x + 2b_4 y + u r^2 - w r = a_4^2 + b_4^2$

We have here 4 simple equations containing the four unknown quantities x, y, u, and w.

x and y determine the origin of the shock. $\sqrt{u}$ equals the absolute velocity v. From v and w we obtain t. Substituting x, y, v and t in the first equation we obtain z.

We have here assumed that the points of observation have all about the same elevation above sea level.

If it is thought necessary to take these elevations into account, a sixth equation may be introduced.

If the propogation of the wave is considered as a horizontal one, as would be done when calculating the position of the *epicentrum* or point above the origin, by means of the times of arrival of a sea wave, the ordinate z of the first five equations would be omitted. Working in this way the resulting four equations viz,

$$2a_1 x + 2b_1 y + um^2 - wm^2 = a_1^2 + b_1^2$$
$$\&c. \qquad \&c. \qquad \&c.$$

remain unchanged.

In the earthquake which we are now considering we see that at Mejillones, Iquique, Cobija, Tocapilla and Huanillos, the arrival of a sea wave seems to have been noted with tolerable accuracy. Through the first of these places, which is the one at which the shock arrived last, rectangular ordinates o x and o y were drawn, and the coordinates of the other places were measured in miles. The coordinates of these places measured in Geographical miles and the times in Iquique time at which the wave reached each, are given in the following table.

	Coordinates		*Time of arrival*
	OX	OY	h.m.
Mejillones ...	a or 0	b or 0	8.46 p.m.
Iquique	a_1 or 150	b_1 or 96	8.40 „
Cobija	a_2 or 36	b_2 or 14	8.38 „
Tocopilla ...	a_3 or 66	b_3 or 31	8.32 „
Huanillos ...	a_4 or 102	b_4 or 58	8.30 „

From this data we see that the times m, p, q, and r respectively equal 6, 8, 14 and 16 minutes. Substituting these values in the four equations

$$2a_1 x + 2b_1 y + um^2 - wm^2 = a_1^2 + b_1^2$$
$$\&c., \qquad \&c., \qquad \&c.$$

We obtain

$$
\begin{aligned}
&1.\quad 300\,x + 192\,y + u\;36 - w\;6 = 3176\\
&2.\quad 72\,x + 28\,y + u\;64 - w\;8 = 1492\\
&3.\quad 132\,x + 62\,y + u\;196 - w14 = 5317\\
&4.\quad 204\,x + 116\,y + u\;256 - w16 = 13768
\end{aligned}
$$

By eliminating w we obtain,

$$
\begin{aligned}
&\text{I.—(from 1 and 2)}\quad 1968x + 1368\,y - 96u = 244776\\
&\text{II.—(from 2 and 3)}\quad 48x + 104\,y + 672u = 21648\\
&\text{III.—(from 3 and 4)}\quad 744x + 632\,y + 448u = 107680
\end{aligned}
$$

By eliminating u we obtain

From I. and II. $1327108x + 929284\,y = 166578200$

From II. and III. $478466x + 378108\,y = 62496700$

$$
\left.\begin{aligned}
\text{Whence }x &= 85.8110\\
\text{and }\quad y &= 56.\ 708
\end{aligned}\right\}
$$

From I $u = 17.40$. ˙ . $v = 45$ feet per second.

Measuring these ordinates upon the map, we obtain a center lying very near 71°. 5′ West Long. and 21°. 22′ South Latitude, a position which is very near to that which has already been obtained by other methods.*

If instead of Huanillos I substitute the ordinates and time of arrival of the sea wave for Pabalon de Pica, another point for the origin will be obtained lying farther out at sea. To obtain the best result, the method to be taken will evidently be, first to reject those places at which it

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* In the proceedings of the British Association for 1858 p. 95 Mr. Mallet quotes the following problem by Prof. Haughton.

Given the times of an Earthquake shock at three places, to determine its horizontal velocity and Coseismal line.

The solution of this is contained in the formula

$$\tan \phi = \frac{a\,(t_2 - t_1)\ \sin B.}{c\,(t_3 - t_2) + a\,(t_2 - t_1)\cos B.}$$

When A B and C are three stations at which a shock is observed at the times t_1 t_2 and t_3, a b and c are the distances between A B and C, and ϕ is the angle made by the coseismal lines x A x, y B y and the line A B, which are assumed to be parallel.

This I applied in the case which has been taken for illustration, but owing to the smallness of the angles between the three stations A B and C, and errors in the time, the result was unsatisfactory. The problem I think ought to be restricted, 1st to places which are a long distance away from a center, and secondly to places which are not nearly in a straight line.

seems likely that some mistake has been made with the time observations, and then with the remaining places to form as many equations as possible, and from these to obtain a mean value. This is a long and tedious process, and as the time observations of this particular earthquake, are probably one and all, more or less inaccurate, it may hardly be worth while to follow the investigation farther as based upon the observations which I have been enabled to obtain.

Errors in Calculations based on Time observations.

When determinations are made by the methods which have just been given, two assumptions are made, first that the time records are correct, and second that the velocity of the shock has been the same to all points where observations have been made. With regard to the obtaining of fairly good observations for time, I think it will be admitted that they present less difficulty than any other observations which can be made upon an earthquake. Also time observations above all other observations are those which are the most commonly made. When a country is shaken by an earthquake the time of the shock is often recorded by thousands of observers situated in various towns. If these records could be collected and then carefully sifted we ought in many instances to be able to form a very fair idea of the time at which a shock reached any given district. A primary source of error in making time observations is the fact that the watches and clocks of the various observers are not correct. A second source of error arises from the fact that different observers may make their observations during different portions of a given shock. Because a wave is transmitted more slowly in water than through rocks, small errors in time observations in calculating the origin of a shock by means of a sea wave, will not be so likely to lead to wrong results, as when we are calculating the position of a *centrum* by means of the times of arrival of a land shock.

With the second assumption we can hardly expect to be working so accurately as might be desired. Whether the velocity of a shock as it radiates from its origin is the same in all directions will largely depend upon the nature and structure of the rocks through which it travels. If the geological structure is the same in all directions between the *centrum* and the shaken places, then our determinations may possibly be correct. It will also be fairly correct if our places lie on an area sufficiently large, so that the distribution of those causes which tend to alter the velocity of a shock, practically balance each other.

In any case where we have reason to believe that our time records are wanting in accuracy or where we suspect that there is a great want in similarity of rock structure between the *centrum* and our points of observation, we are liable to find considerable errors in our determination. Whilst pointing out errors which this method of determination is liable to, it is only fair to state that all other methods which depend upon time observations appear to be open to similar objections.

Another error which we are possibly liable to when determining the elements of an earthquake movement, is using the true and horizontal velocities as if they were identical,—an assumption that may only be practically true when the *centrum* is near the surface, or the places of observation are remote from the origin.

Again it is often assumed that the origin is a point, whereas it may be a cavity or fissure, and also that the waves are spherical.

In calculating, we usually consider the places which have been shaken as lying on a plain, whereas if we wished to be accurate we should make allowances for the sphericity of the earth and the differences of elevation due to mountains or depressions. These however are points, the consideration of which, is in all probability of small importance.

Whether an earthquake disturbance as it spreads from an origin, even in materials which are practically homogeneous has a constant velocity, or a whether, the principal motions which affect us travel *directly* from the origin or only radiate from the *epecentrum*, are points which might be discussed.

To determine the velocity of the sea wave and the time at which the shock originated.

If we take the last determined position as being the origin, then by comparing the difference in the distance between this origin and the various places which were affected by the earthquake, with the differences in the times at which they were severally shaken, we have the means of determining the velocity with which the motion of the earthquake was propagated. To determine the velocity with which the sea wave was propagated we must take the difference in the times of its arrival at the several places. In the first column of the following table, the difference in distance from the origin of the three places which are mentioned and Huanillos are given.

In the second column the differences in time between the time at which the first wave reached Huanillos and the places which are mentioned are given. In the third column the velocity of the sea wave as calculated from the first and second column.

	Diff. in distance.	Diff. in time.	Velocity.
Mejillones... ...	63 miles	16 min.	346 ft. per second
Iquique	39 „	10 „	343 „ „ „
Cobija	33 „	8 „	363 „ „ „

The mean of these three velocities is about 350 feet per second.

To have determined this velocity more accurately, a number of places, to reach which the wave travelled over an area which was almost uniform in depth, ought to have been taken. For each possible pair of these places a velocity might have been determined the mean of which would have been a mean velocity.

In order that the wave should have reached the above mentioned places at the times which have been given, because we can measure the distance of these places from the place at which the shock is supposed to have taken place, it is easy to calculate that the wave must have originated at about 8.19 p.m. in Iquique time, or 8.15 local time.

In conclusion to this part of my paper, I beg to remind the readers of this article that it has been written as much for the purpose of illustrating methods of determing the center of an earthquake disturbance as to give the particulars of the special earthquake which has been spoken about.

Because I felt that the data with which I was working, especially with regard to the accuracy of the times of arrival of the shocks and sea waves, were by no means absolutely reliable, I have not paid attention to strictness in the details of arithmetical work. Nevertheless I think that the determination of the center of the shock and the time at which it occurred are probably much nearer the truth than anything which could have been obtained by mere inspection of the data.

Some of our readers may object to the assumptions which I have made in these determinations, and that objections can be raised is quite evident. Objections may be made to the mathematical solution of very many geological problems, the reason chiefly being that the data which a e used are so indefinite that it becomes impossible to fully recognize or grasp the meaning of the varied circumstances they present. Nevertheless I must say that the approximate results which they present us with, are in all probability very ofton superior to anything which can be obtained by processes of ordinary reasoning.

Part III.

Notes upon Sea waves produced by Earthquakes.

It has just been shown that the Peruvian earthquake of May 11th, 1872, took place at or near a spot lying in Lat. 21° 22′ S. and 71° 5′ W. Long. at about 8.15 p.m. local time.

Shortly after this date various ports along the Western shores of South America were inundated by a series of large sea-waves.

Still later, but at varying intervals, the western shores of North America, the Sandwich Islands, New Zealand, Japan and other places in the Pacific Ocean were also visited by a series of waves, but of less intensity than those which committed so much havoc in the neighbourhood of Iquique. The names of many of the places which were inundated and details of the appearances presented by the waves which reached these places have been given in the first part of the paper.

Differences in the Heights of the Waves.

The first point which may be noticed is that at different places the waves were of different heights. The differences in height observed between places far apart, is evidently due to the gradual enfeeblement of the actuating force as it put fresh particles of water in motion. The difference in height observed between places lying near together is probably due to the configuration of the coast, the interference of outlying islands, reefs, &c., causes which would produce somewhat similar effects in the heights of tides.

The difference in height between successive or different waves is rather more difficult of comprehension.

In order to obtain some idea of the manner in which a wave is propagated, imagine a ball to have been dropped into a still pond. When the ball first begins to enter the water it will crush it outwards on all sides, and a wave will be raised to flow away over the surface and raise the level of the pond.

Because water is practically incompressible it is probable that the ball will not enter the water more quickly than that which comes in contact with it, can be raised upwards to form a wave.

The first wave may therefore be supposed to be due to the water being crushed outwards. The second, third and following waves will be those which are formed after the ball has passed beneath the surface, and they will be due to the particles of water which have been driven outwards swinging together and clashing at a central point. In the case of the earthquake shock, the first surface wave may have been produced by the upheaval or depression of the water lying above a certain point, whilst the succeeding waves would be like the succeeding waves produced by the ball.

As the action which produces these waves continues, the energy which was imparted to any particle of water will on account of the work which it has to do in displacing its neighbours through frictional resistance, gradually grow less and less until it finally dies away. The waves which are the result of this motion must also grow less. Now a high wave travels more quickly than a low one. For this reason, all the waves of which we speak are small in comparison with the depth of the ocean, and it is only for waves whose depths are comparable with the depths of the ocean that the law for velocity of waves is true, according to which all waves travel at the same rate, but when the waves are all small, the larger and higher travel more quickly than the others.

Now for small waves the velocity depends upon the square root of their lengths, but with larger waves such as are produced by an earthquake the velocity does not depend upon this law, but upon the square root of the depth of the water. As compared with the smaller ones they travel more quickly. Thus in water 10,000 feet deep a wave 10 feet long travels at the rate of 7 feet per second whereas a wave 100,000 feet long travels at the rate of 534 feet per second. If therefore we have sea waves produced by a single disturbance we shall have a series of waves of unequal magnitude produced, and these will travel with different velocities.

If however we have the sea waves produced by a series of disturbances of unequal magnitude it seems possible that those of an early disturbance might be overtaken and thus interfered with by a series which followed.

These considerations may perhaps help us to understand the appearances which were observed at many localities.

It will be noted that the greatest waves were observed in the neighbourhood of Huanillos and Tocopilla where they were 60 to 80 feet in height. At places lying North or South from these, the heights were less and less, until at places far away, as at San Francisco they were only 9 inches in height.

At several places, small waves or disturbances in the water were observed to precede larger ones, as at Channeral, Arica, and Callao. At other places like Hilo, and Kahului small waves were interposed between larger ones. At one or two places where the large waves were observed the intervals of time between their coming appear to have been irregular.

At places where the intervals of time between waves which were small were observed, as in Japan, they appear to have had a regular succession.

At Concepcion and at San Francisco, before the waves came in, the sea appears to have drawn back. In all probability this phenomenon occurred at most places, but not having been observed was not recorded. The explanation probably lies in the fact that whenever a wave is produced a certain quantity of water must be drawn from the level which surrounds it, in order that it should be formed, and as a wave advances towards a shore, this is drawn from the shore line. Out in the open ocean it is drawn from the hollow which intervenes between two waves. As has been pointed out by Mr. Darwin, it is like the drawing of the water from the shore of a river by a passing steamer. By reference to the first part of this paper the heights of waves and the intervals of time between their arrivals at several points where observations were made can be seen. In considering these waves we must remember that from the way in which the wave originates at the bottom of the ocean it can not be considered as a true wave until it has traveled some distance, nor can its velocity be accurately calculated from the depth.

Whilst endeavouring to explain the anomalies which exist in the coming of the waves, we must remember that owing to the configuration of the ocean bed or the coast line, reflected waves may have been produced which may either have been observed as separate waves or as waves which were compounded with others coming direct from the origin. We may also suppose that series of waves were produced at unequal intervals by unequal forces, a view which receives conformation by a reference to the land-shocks, which were experienced in the vicinity of Iquique.

Velocity of Propagation.—In the 8th column of the following Table will be seen the rate at which the wave travelled from the origin to various places along the shores of the Pacific. The distances from these places to the origin, were, for those which lay along the South American coast, measured from a map constructed by orthographic projection. The distances of the other places like those in Japan were calculated as arcs of great circles.

In the paper by Dr. Geinitz (Das Erdbeben von Iquique am 9 Mai 1877 und die dadurch erzeugte Fluth im Grossen Ocean. Von Dr. E. Geinitz in Göttingen Petermann's Geogr: Mittheilungen 1877 Heft XII p. 454) calculations of a similar nature are to be found.

	Longitude	Arrival of Wave Local Time.	Diff. of times with Greenwich.	Greenwich Mean Time.	Time taken by Wave.	Time in Seconds.	Distance from the origin in miles.	Velocity in feet per Second.	Depth of the ocean in Feet.	Height of Waves.	Interval between Waves in minutes.
		Dy. H. M.	H. M.	Dy. H. M.	H. M.						
Origin of Wave ...	71°. 5′ W.	11. 8.15	4.44	9.12.59							
San Francisco......	122°. 32′	9.18.18	8.10	10. 2.28	13.29	48540	4578	498	7721	9 in.	
Callao	77°. 15′	9.12. 0	5. 9	9.17. 9	4.10	15060	658	231	1657		
Iquique	70°. 14½′	9. 8.40	4.41	9.13.21	.22	1320	87	348	3770	20 ft.	22
Cobija	70°. 21′	9. 8.38	4.41	9.13.19	.20	1200	80	352	3857	30 ft.	
Mejillones	70°. 35′	9. 8.45	4.42	9.13.27	.28	1680	108	339	3587	35 ft.	15 or 45
Chanaral	71°. 34′	9.10.40	4.46	9.15.26	2.27	8820	455	272	2309		10
Coquimbo	71°. 24′	9.10.30	4.45	9.15.15	2.16	8160	508	328	3363		30
Valparaiso	71°. 38′	9.11.30	4.46	9.16.16	3.17	11820	695	310	3000		
Concepcion	73°. 5′	9.12. 0	4.52	9.16.52	3.53	13980	928	350	3824	ft.	12 to 15
Honolulu...........	157°. 55′	9.17.20	10.32	10. 3.52	14.53	53580	5694	561	9807	34 to 54	25
Hilo	155°. 3′	9.16.45	10.20	10. 3. 5	14. 6	50760	5506	563	10217	{30 or 8	3 or 15 18 or 27
Kahuliu	156°. 43′	9.16.45	10.27	10. 3.12	14.13	51180	5611	579	10437		
Samoa	171°. 41′W.	9.16.30	11.27	10. 3.57	14.58	53880	5773	566	9972	12 ft.	10
Tauranga	176°. 11′ E.	10.20. 0	11.45	10. 8.15	19.16	69360	5615	427	5697		
Wellington...	174°. 30′	10.19. 0	11.38	10. 7.22	18.23	66180	5574	445	6168	11 ft.	10
Akaroa	172°. 59′	10.19. 0	11.32	10. 7.28	18.29	66540	5542	440	6031		
Lyttleton...........	172°. 45′	10.19. 0	11.31	10. 7.29	18.30	66600	5558	441	6055		
Kamieshi	140°. 50′	10.22. 0	9.23	10 12.37	23.38	85080	8844	549	9378	6 ft.	15
Hakodate	140°. 50′	10.23.30	9.23	10.14. 7	25. 8	90480	8778	512	8169	7 ft.	20

NOTE.—In the second part of this paper the Velocities with which the wave travelled to Iquique, Cobija, and Mejillones were respectively given as 343, 363 and 346 feet per second.

From the following table we see the *average* rates at which the wave was transmitted.

1	South American coast...	316 feet per second.
2	Sandwich Islands	567 „ „ „
3	New Zealand	438 „ „ „
4	Japan	530 „ „ „

It will be observed that for the longer distances the velocity was greater than for the shorter ones, as it ought to be on account of the greater depth of water.

Depth of the Ocean.—If a very long wave is transmitted along a trough of uniform depth, the velocity of the wave, v, holds a relation to the depth, h, which is expressed in either of the following formulæ.

$$h = \frac{v^2}{g} \quad \text{or} \quad h = \left(\frac{v}{k}\right)^2$$

where (as given by Dr. Geinitz)

$$g = 32.1908 \text{ and } k = 5.671$$

It will be observed that these two formula (the first of which is known as Russell's formula and the second as Airy's) are practically identical. The apparent difference is in the average value assigned to the constant.

Airy in the Encyclopedia Metropolitana *(Tides and Waves)* investigates the complete formula which may be put in the shape

$$v^2 = \frac{lg}{2\pi} \; \frac{\varepsilon^{\frac{4\pi h}{l}} - 1}{\varepsilon^{\frac{4\pi h}{l}} + 1}$$

v being velocity of wave in feet per second.
l length of wave in feet.
h depth of water in feet.

$$\pi = 3.1416$$

It will be observed that when l is great in comparison with h this complete formula becomes what is commonly known as Airy's or Scott Russell's. As in all earthquake waves observed, the time of a complete rise and fall is generally about 20 minutes, the length of such waves is usually more than 20 × 60 × say 500 feet, so that the simpler formula is applicable.

To put this more clearly; the complete formula may be put in the shape

$$h = \frac{l}{4\pi} \log_{\epsilon} \frac{lg + 2\pi v^2}{lg - 2\pi v^2}$$

Remembering that $\frac{v^2}{l}$ is very small, we may expand the exponential, and we find on simplifying,

$$h = \frac{v^2}{g} \left(1 + \frac{4\pi^2 v^4}{3\, l^2 g^2} + \text{Smaller terms}\right)$$

So that the depth obtained by Scott-Russell's rule must be increased by the fraction of itself $\frac{4\pi^2 v^4}{3 l^2 g^2}$.

If we take 30 minutes, say, as the time of a complete oscillation, then $l = 30 \times 60 \times v$, and the fraction becomes about $\frac{1}{1500}$ for such velocities as are here involved.

In the calculations made by Dr. Geinitz the formula of Russell and Airy are used as if they were distinct equations, and with each of them a slightly different depth is deduced for the same stretch of ocean. Farther, the value of g is taken as being constant over the surface of the earth. For these reasons, and more especially because the position of the origin of the shock, and the time of that origin are different to those determined by Dr. Geinitz, I have ventured to repeat and extend the calculations.

From the formula 32.008 $(1 + .005133 \text{ Sin.}^2 \lambda)$ an average value for g has been calculated as follows:

Between Latitudes 18° S. & 36° S. for S. America	Lat. 27°	S.	g	= 32.120
Between S. America & San Francisco	Lat. 37°	N.	,,	= 32.119
,, ,, ,, Sandwich Islands	Lat. 21°	N.	,,	= 32.105
,, ,, ,, Samoa	Lat. 13°49′	S.	,,	= 32.093
,, ,, ,, New Zealand	Lat. 41°	S.	,,	= 32.139
,, ,, ,, Japan	Lat. 41°	N.	,,	= 32.122

The results of the calculations made by means of the formula $h = \frac{v^2}{g}$ are given in the table on page 82.

The *average* depths of the ocean between the origin and the following places are as follow:

1	South America	3171	feet.
2	Sandwich Islands	9953	"
3	New Zealand	5988	"
4	Japan	8773	"

From the phenomena which attended this earthquake it would seem as if it were the result of some great volcanic movement, and from the calculations which have been made it would seem that the situation of the scene of this movement is at a place some distance out from the South American coast beneath deep water. From other earthquakes which have taken place it would seem that it is not unlikely that there is a line parallel to the S. American coast along which similar disturbances have taken place, that is to say along a line which forms the angle beneath a tolerably level ocean floor and the land which slopes steeply up towards the Andes.

General Notes on Sea Waves of the Pacific.—From the following notes it will be seen that sea waves in the Pacific Ocean are by no means of uncommon occurrence. When we consider that this great ocean is not only fringed with bands of volcanic mountains, but has its surface studded with active or extinct craters which are unparalleled in number and in size, and that all these indicate to us the existence of a pent up energy, we see that earthquake shocks giving rise to sea waves might naturally be expected, and if we look to records we find that such phenomena are by no means uncommon.

Taking the coast of South America alone, I find that more than 71 severe earthquakes occurred, since the year 1500, and many of these are specially mentioned, as having been accompanied by sea waves which in many cases were larger than those which we have here been writing about. For a description of these earthquakes see Geographical Magazine, Aug., 1877, p. 207. If we look to the records of the sea waves which have originated near Japan we shall find an equal number. And if it were possib'e to collect all the records of the earthquakes in the Pacific Basin which were sufficiently great to produce sea waves, I feel sure that we should find them numerous enough to excite feelings of surprise.

The wave of 1868.—In 1868, Aug. 11th, a sea wave ruined many cities on the South American coast, and 25,000 lives were lost. This wave, like all the others, travelled the length and breadth of the Pacific.

In Japan, at Hakodate it was observed by Capt. T. Blakiston, who very kindly gave me the following account:

On Aug. 15th at 10.30 a.m. a series of bores or tidal waves commenced and lasted until 3 p.m. In 10 minutes there was a difference in the sea level of 10 feet, the water rising above high water and falling below low water mark with great rapidity. The ordinary tide is only 2½ to 3 feet. The disturbance producing these waves originated between Iquique and Arica in about Lat. 18.28 S. at about 5 p.m. on August 13th. In Greenwich time this would be about 13 hr. 9 m. 40 sec. August 13th. The arrival of the wave at Hakodate in Greenwich, time would be about 14 hr. 7 m. 6 sec. August 14th: that is to say the wave took about 24 hrs. 57 m. to travel about 8700 miles, which gives us an average rate of about 511 feet per second. These waves were felt all over the Pacific. At the Chatham Islands they rushed in with such violence that whole settlements were destroyed. At the Sandwich Islands the sea oscillated at intervals of 10 minutes for three days.

Comparing this wave with the one about which I have more specially been writing, we see that one reached Hakodate with a velocity of 511 feet per second, whilst the other travelled the same distance at 512 feet per second.

An account of this earthquake wave has been given by F.v. Hochstetter (Über das Erdbeben in Peru am 13. August 1868 und die dadurch veranlassten Fluthwellen im Pacifischen Ocean; Sitzungs-Berichte der Kaiserl, Akademie der Wissenschaften. Wien, 58. Bd. 2. Abth 1868). From an epitome of this paper given in Petermann's Geograph: Mitt: 1869 p. 222 I have drawn up the following table of the more important results obtained by F.v. Hochstetter. The wave is assumed to have originated near Arica.

	Distance in sea miles from Arica.	Time taken by Wave.	Velocity in feet per sec.	Depth of Ocean in feet.
		h. m.		
Valdivia	1420	5. 0	479	7140
Chatham Island	5520	15.19	608	11472
Lyttleton	6120	19.18	533	8838
Rapa	4057	11.11	611	11598
Newcastle	7380	22.28	538	9006
Apia (Samoa)	5760	16. 2	604	11346
Hilo	5400	14.25	555	9568
Honolulu	5580	12.37	746	17292

Although the velocity with which the wave of 1877 traversed the Pacific Ocean to Hakodate is the same as that for the wave of 1868, the rates at which it travelled to Lyttleton, Samoa, and Honolulu are considerably less, and consequently the calculated depths of the ocean between South America and these places are also less. This difference in velocity appears to me to be partially due to Arica having been taken as the center of the shock, although the great sea wave was seen to come in about 20 minutes after the first great shock. If the origin of this shock like that of the wave of 1877 was some distance out at sea, as it appears to have been, then the time at which the first wave was formed would have been earlier, and also the distances to the places on the opposite side of the Pacific would have been less, both of which would tend to reduce the velocity, and consequently the calculated depths of the ocean which depend upon the square of this velocity would also be reduced.

The wave of 1854.—This wave originated near Japan and it was recorded on tide gauges at San Francisco, San Diego and Astoria.

A copy of these records may be found at the end of the U. S. coast survey reports for 1855, and on p. 342 of the same volume these are discussed by Prof. A. D. Bache.

From this report we learn that on Dec. 23 at 9.15 a.m. a strong shock was felt at Simoda in Japan, which at 10 o'clock was followed by a large wave 30 feet in height. The rising and falling of the water continued until noon. Half an hour after this, the movement was more violent than before. At 2.15 the agitation was less, and at 3 p.m. it was comparatively slow. Altogether there were 5 large waves.

On Dec. 23 and 25, unusual waves were recorded upon the self-registering tide gauges at San Francisco, San Diego and Astoria.

At San Francisco three sets of waves were observed. The average time of oscillation of one of the first set was 35 m. whilst one of the second and third sets was almost 31 m.

At San Diego three series of waves were also shewn, but with average times of oscillation of from 4 to 2 m. shorter than the waves at San Francisco.

The San Francisco waves appear to indicate a recurrence of the same series of phenomena.

The record at San Diego shews what was probably the effect of a series of impulses, the heights increasing to the third wave, then diminishing, then once more renewed, after which it died away.

From Simoda to San Diego it is 4917 nautical miles. The time of transmission was 12 hr. 13 m, which gives for the rate of motion, 370 miles per hour or, 6.2 miles per minute, or 545 feet per second.

From Simoda to San Francisco it is 4527 miles. The time of transmission was 12 hr. 38 m. which gives for the rate of motion 358 miles per hour, or 6.0 miles per minute, or 528 feet per second.

From the rate of motion and the duration of an oscillation the length of the wave on the San Francisco path was

210 or else 217 miles, and on the San Diego path 186 or 192 miles.

From the length of the wave and its velocity, we have an average depth for the San Francisco path of 2230 fathoms or 2,500 fathoms, according as we reckon the length to have been 210 or 217 miles.

The corresponding depth for the San Diego path is 2,100 fathoms.

Comparison of Velocities of wave transit which have been actually observed, with velocities which ought to exist from what we know of the depth of the Pacific by actual soundings.

From a chart given in Pettermann's Geograph: Mittheilungen, Band XXIII p. 164, 1877, it is possible to draw approximate sections on lines in various directions across the bed of the Pacific.

From the origin of the shock to Japan (Kamaishi) the line would be as follows.

about	7,441 miles	15,000 ft. deep
	1,100 „	18,000 „ „
	160 „	27,000 „ „
	80 „	12,000 „ „
	60 „	6,000 „ „

On account of the Tuscarora and Belkap Deeps this would be the most irregular line over which the wave had to travel.

From the origin to New Zealand (Wellington) the line would be

about	5,274 miles	15,000 feet deep
„	300 „	12,000 „ „

From the origin to Samoa the line would be

about	5,773 miles	15,000 feet deep

From the origin to the Sandwich Islands (Honolulu) the line would be

almost	5,634 miles	15,000 feet deep
and	60 „	12,000 „ „

By Scott-Russell's rule or what is almost identically the same, by Airy's general formula, we can calculate how long it would take such waves as we have been speaking about, to travel over the different portions of each of these lines and by adding these times together we obtain the time taken to travel across any one line. I have made these calculations, but as I get in every case answers which are too small I think it unnecessary to give them.

The actual times taken to travel the distances just referred to, were,

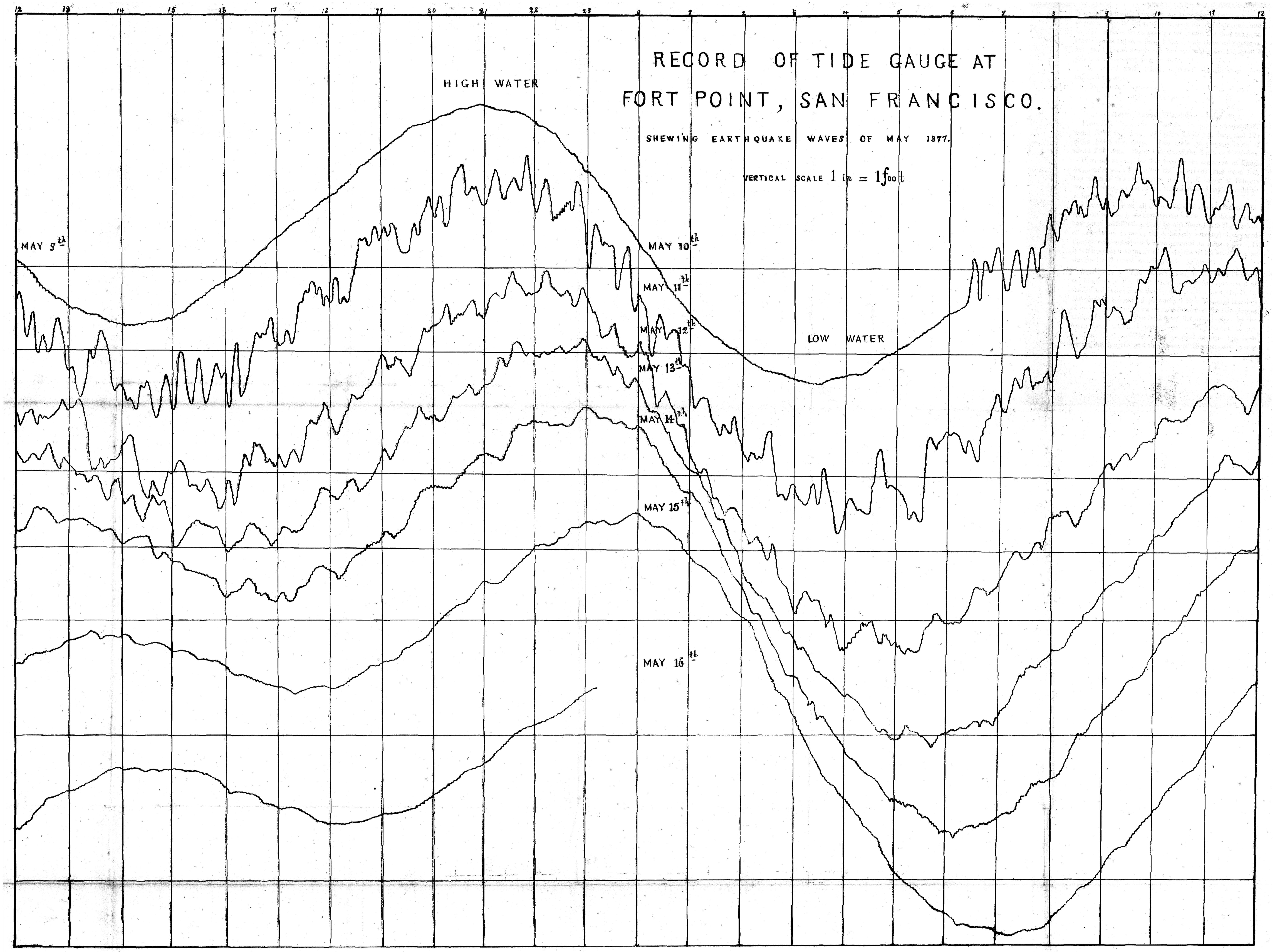
To Japan (Kamieshi)	23 hr. 38 m.
„ New Zealand (Wellington)	18 „ 23 „
„ Samoa	14 „ 58 „
„ Sandwich Islands (Honolulu)	14 „ 53 „

From San Francisco to Simoda the line is almost 3,567 miles 3,000 fms. deep, 840 miles 2,500 fms. deep, and 120 miles 1,000 fms. deep. This gives an average depth of about 2,854 fms. Bache calculated the depth at 2,500 fms.

If we are to consider that because the sea-wave at Simoda came in some time after the land shock had been felt, the origin of this earthquake instead of being at Simoda was some distance out at sea, this calculated depth would be reduced.

I have now given all the available materials for calculations concerning these earthquake waves, and have shown that some modification must be introduced into the method of calculation to make the ordinarily accepted theory and the observations which I have assumed as facts agree. Is it not possible that many of the depths which are given as the results of actual soundings, are too great?

Importance of Tide Observations in Japan.—Through the kindness of Mr. C. P. Patterson, the Superintendent of the United States Coast Survey Department, and Mr. D. G. Davidson of the same department, I have obtained tracings of several earthquake waves as recorded on the tide gauges at San Francisco. The tracing of the record given by the earthquake which I have been writing about, is appended. For convenience the original diagram has been cut up into lengths, and the curves of the successive pieces


RECORD OF TIDE GAUGE AT
FORT POINT, SAN FRANCISCO.
SHEWING EARTHQUAKE WAVES OF MAY 1877.
VERTICAL SCALE 1 in = 1 foot
HIGH WATER
LOW WATER
MAY 9th
MAY 10th
MAY 11th
MAY 12th
MAY 13th
MAY 14th
MAY 15th
MAY 16th

placed on one sheet below each other. In its general appearance, this curve is very similar to the records of other earthquake waves. The large waves represent the ordinary 6 hours rise and fall of the tide. Usually these are fairly smooth curves. Superimposed on these large waves are the smaller zigzag curves of the earthquake disturbance, lasting with greater or less intensity for a period of six days. As these curves are reproduced as recorded, and are drawn to scale horizontally for hours, and vertically one inch to the foot to shew the extent of the rise and fall,—verbal description is hardly necessary to explain their meaning.

To those who are studying earthquakes, the importance of a diagram of this description is too evident to be commented on.

If a few self-registering tide gauges could be established on the coast of Japan, the results tending to the advancement of Seismology, Geology, and most important of all, Hydrography, would be both numerous and valuable.

In a country of earthquakes and volcanos like Japan, it is not improbable that from time to time we should obtain records of many submarine disturbances which are now passed by unnoticed. By studying the relative sizes and periodicity of the waves upon our diagrams we should learn something of the nature of the convulsions. By comparing the diagrams of one station with those of another, the position from which these disturbances originated might be calculated and important inferences made as to the depths of the ocean. Physicists would have in these records the means of studying wave motions on a scale far beyond the reach of European investigators.

If three self-registering tide gauges were established in Yedo Bay and the records of these three gauges were compared, say in successive years for tides having the same total rise, and increasing and diminishing in like manner, it would seem that we should have a method which, so far as I am aware, has never yet been adopted, for determining the *relative* rise or fall which is taking place in the land where our stations are situated. One means of accomplishing this would be for the observers at each of the stations to determine the height of certain fixed points in the rocks relatively to say high water mark. If during successive years we found that (the tide being in the same condition) the *differences* between the measurements taken at the different stations had varied, we should have in the difference of these differences a measurement of relative rise or fall.

As an indication that during the recent times the rise of the land round the shores of Yedo Bay has been very rapid, I may state that at many places we have existing in soft easily disintegrating tuff rocks, fresh borings of *lithodomi* 6 to 10 feet above the present high water mark.

The object in taking three stations for making observations of this description is that in addition to telling us that an upward or downward motion is going on, they would give to us the axis of that movement, or the line along which the motion is at a maximum.

Not only would observations of this description give us a unit wherewith to assist us in the measurement of geological time, but by carefully mapping and measuring all the faults which are so well exposed around the shores of Yedo Bay and comparing the notes thus obtained with similar notes obtained some year's hence, we might possibly arrive at some connection between elevation and faulting, and also between faulting and the earthquakes we so often feel. Whilst observing tides, studying sea-waves and correlating phenomena like elevation, faults and earthquakes, other results more practical in their nature would be obtained. By combining with the tide gauge the means of recording waves, approaching storms might be foretold. The effect of winds in piling up the water would be observed and measured, and above all Japan which has already become a nation of great maritime importance and is destined to be still greater, would obtain for itself a record of the motion of its waters and confer a boon upon its navy and mercantile marine. There is perhaps no country in the world where so much is to be learnt from the study of the tides as in Japan, and the phenomena which this study will make clear, are so plainly set before us, that an attempt at their solution appears before us as a duty. The waters which surround Japan appear to be the only portion of the empire which has been overlooked—with geologists and miners the capabilities of the land have been examined—with the telescopes of well equipped observatories the heavens above the land are being gauged, and all that remains to be done is the examination of the phenomena of the waters which surround the land.

When this has been accomplished, and it is only a question of time as to when it will be commenced, the survey of Japan will be completed.

Conclusion.

Notwithstanding the fact that many attempts have been made to bring earthquake and Volcanic phenomena with which they are apparently so closely connected, within the bounds of rule, so far, the results of our studies in this direction have not been very satisfactory.

Although the elastic waves produced in the crust of the earth by the attraction of the heavenly bodies, which no doubt is greatest when several are acting in conjunction, are effects produced by causes which act with a regularity which is calculable, the materials on which these forces are brought to bear are so irregular in their nature and in consequence of processes degradation and other causes are ever varying in their character, it does not seem to be possible that we shall be ever able to obtain satisfactory results from the materials which are present at our hand. Dana illustrates the occurrence of earthquakes by the crackling of a stove pipe. A stove pipe is regular in form and when it cools it gives out its heat according to a known law. The forces of contraction which are acting upon the pipe are tolerably regular, but the cracklings which take place are, like the snaps and jars upon the earth, so uncertain in their action, that were we to attempt to correlate them with the producing cause, we should feel that we had before us a task of difficulty.

If then we can not yet predict the coming of an earthquake, can we in any way ward off its evil effects?

The Japanese god at Ise when he was consulted as to what was best to be done at the time of an earthquake, replied that when a sea wave came, people were to run to high places, but when it was a landshock to a bamboo grove.* The people grumbled because they felt that advice like this was not better than that which could be obtained from ordinary mortals. Nevertheless it is only advice like this which can be followed by a persons overtaken by these calamities.

In many cases disastrous effects may be warded off by properly constructed buildings.

When earth shocks of great severity suddenly occur it is but little that can be done, and before we can reach the bamboo grove the tiles may be falling down about our ears.

With the sea wave however, in these modern days when so many places are able by electrical connections instantaneously to communicate with each other, it does not seem impossible that hundreds of places should be forewarned of its coming, and their inhabitants have opportunity to prepare themselves against its disastrous effects. Thus for instance in the case of the wave about which I have been writing, it was from 18 to 25 hours after it had produced its devastation along the south American coast, before it had travelled across the Pacific and rose upon the shores of countries like Australia and Japan.

If the thousands of fishermen who reside along the Eastern coast of Japan could have been warned of its coming, and this by telegraphic communication would have been an easy matters, much property would have been saved and

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* In a bamboo grove the ground is so interlaced with roots, that it would be difficult for it to be split open.

sudden alarm avoided. I feel that this suggestion, if it were carried out, might possibly be the means of mitigating some of those disastrous calamities so ever recurrent upon the shores of the Pacific.

In the results which I have laid before the members of the Seismological Society, I have only referred to *mean depths* of the ocean, but when observations have been made upon several lines which intersect each other, it is evident that something closely approaching to actual depths ought to be obtained.

NOTE.—Since the above was printed, through the kindness of Dr. E. Naumann I have seen a copy of a second paper by Dr. Geinitz on the earthquake of 1877 (Nova Acta der Ksl. Leop.-Carol-Deutschen Ackademie der Naturforscher. Band. XL q. Nr. q.) In this paper, which is more elaborate than the first, containing many additional observations, the depths of the ocean between South America (Iquique) and various points in the Pacific are considerably reduced, as will be seen from the following table.

	1st Paper.		2nd Paper.	
Apia	2225	becomes	1930	fathoms.
Hilo	2325	„	2310	„
Kamaishi	2389	„	2184	„
Hakodate	2150	„	1818	„ .

On the other hand, certain depths have been slightly increased.

As a result of these second calculations Dr. Geinitz considers that the calculated depths of the ocean and those obtained by actual soundings are in accordance, a result which is diametrically opposed to that which I have obtained.

This difference between my calculations and those of Dr. Geinitz, Hochstetter and others, chiefly rests on the origin we have assigned for the sea-waves. Dr. Geinitz for instance, although he says that the origin of the 1877 earthquake was not on the continent but to the west in the ocean, bases all his calculations on the assumption that the *centrum* was at or near to Iquique, and the time at which that city was disturbed, was the time at which the waves commenced to spread across the ocean. This time is 8.25 p.m. At this time, however, it appears to me that the waves must have been more than double the distance between the true origin and Iquique, from Iquique on their way towards the opposite side of the Pacific. Introducing this element into the various calculations which have been made respecting the depth of the Pacific Ocean as derived from observations on earthquake waves, which element, insomuch as the waves appear to have come in to inundate the land some time after the shock, needs to be introduced, we reduce the velocity of transit of the earthquake wave and consequently the resultant depths of the Ocean.

In Dr. Geinitz's paper there are also some slight differences in the times at which the earthquake phenomena were observed at various localities. These, however, are but of minor importance. At the end of the paper by Dr. Geinitz two interesting tide gauge records are introduced, one from Sydney and the other from Newcastle. These appear to show a marked difference in the periods of the sea-waves at these two places.